PICSC FINAL REPORT

1. Administrative

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Project Title: Empirical projection of future shoreline position and inundation due to sea level rise
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2. Public Summary

Chronic erosion leads to loss of property and critical habitats, and it restricts public access along developed coasts. There are, currently, no practical methods for estimating the spatial extent of erosion hazard, despite the fact that increased sea level rise (SLR) over the current century is likely to contribute toward more land being exposed to future erosion. This study creates a new model which provides estimates of exposure to erosion on a local geographic scale. This new method is a valuable tool for the coastal community because of its ease of implementation and because it uses historical shoreline trends, information that is widely available.

This study applies the new model to all sandy shorelines of the Hawaiian Island of Kauai. Application to an entire island serves to: 1) ensure that the model can be successfully applied to diverse geologic and wave settings; and 2) provide erosion hazard projections for improved coastal management both for Kauai County and as part of the Hawaii legislatively-mandated Act 83, which requires the creation of the Interagency Climate Adaptation Committee (ICAC) tasked with creating a climate adaptation report on the impacts of SLR.

Modeled erosion hazard areas are graphically presented in map form to identify areas that are vulnerable to erosion and which can be used to improve the decision-making process in coastal management. The probability of future exposure to erosion is shown as geographic information system (GIS) layers. These layers are incorporated into an online tool that displays erosion hazard layers, along with other SLR-related hazards. The website (http://www.pacioos.hawaii.edu/shoreline/slr-icac/) is currently password protected while this tool is in draft form; public release is expected at the end of year 2017.

Erosion hazard layers for the years 2030, 2050, 2075, and 2100 were created for all sandy shorelines of Kauai Island, Hawaii under the IPCC “business-as-usual” SLR scenario. Results for Kauai indicate that all four regions of the island (North, East, South, West) will have more areas experiencing coastal retreat, and the rates of retreat will become more intense over the current century. The percent of Kauai shorelines included in the study that show retreat (those with a negative long-term shoreline change trend) increased from 73% historically, to 86% by the year 2050, to 91% by the year 2100. Erosion hazard layers produced by this study will be widely available to government agencies and the general public, and will be essential in assessing vulnerability to erosion with increased SLR.

3. Technical Summary

Recent maps of historical shoreline change and vulnerability to flooding due to SLR are improving understanding of shoreline variability and the effects of climate change. However, significant gaps remain in our ability to plan for increasing coastal erosion with expected accelerations in SLR. The goal of this project is to use historical shoreline change data to identify the influence of both sediment supply and rising sea level on shoreline stability. This data will be combined with an engineering model that predicts shoreline erosion with SLR, but neglects to account for the role of sediment availability in modulating shoreline position.

Under assumed scenarios of SLR, a hybrid model will be used that integrates the historical shoreline trends with future (engineering model-based) projections. Although simple in concept, this approach has never been tried before. This study develops an easily transferable methodology and planning tool that can form the basis of a climate-ready strategy of beach management. Using data and maps (which will be produced by the project), decision-makers will be able to prioritize beach conservation efforts, screen permit applications, identify potential future impacts, and increase the resiliency of the current management network of decision-making. By planning for future beach response to SLR, this project will allow for the existing decision-making system to evolve new strategies focused on adaptation to future SLR.

Model creation and testing was completed successfully and published in the journal *Natural Hazards* (Anderson et al., 2015). The model was applied to all sandy shorelines of Kauai and is being used to assess environmental and economic impact for the Hawaii legislative report on SLR impacts. This project made estimates of exposure to future erosion with increased SLR available for the legislative report, for government agencies to use in future planning initiatives, and for general public information. The study is also the first to quantify the possible effects of increased SLR on coastal retreat. Model results indicate that by mid-century, the average amount of recession nearly doubles with increased SLR compared with the amount of retreat if SLR followed historical rates. These findings highlight the need for early mitigation and planning.

4. Purpose and Objectives

The goal of this study is to model beach response to rising sea level over the 21st century. This project completes ongoing development of a transferable methodology for all Hawaii beaches, which will allow advanced planning for: 1) identification of future erosion hotspots, trouble areas, management concerns, community issues, and ecological conservation demands; 2) collision between migrating shoreline and upland development that will trigger permit requests for potentially damaging shoreline protection; and 3) SLR adaptation measures, such as roadway relocation, beach park redevelopment, public access planning, and land protection.

Since this project had already begun under separate funding from the Hawaii Department of Land and Natural Resources (DLNR), model development was already well underway. Thus, the primary goal of this project was to apply the model to all sandy beaches of Kauai except for the Na Pali Coast, and produce GIS-compatible layers depicting future erosion hazard zones, coastal geology (http://pubs.usgs.gov/of/2007/1089/; proxy for upland "erodibility"), tax-map-key data, passive inundation on digital elevation models (DEMs), and other GIS layers as deemed important by our partners.

There have been no changes to the original objectives; yet, some adjustments were made to the format of deliverables. After discussions with DLNR, the venue for display changed from maps, in atlas format, to an online viewer administered by the Pacific Islands Ocean Observing System (PacIOOS). The production of GIS layers will continue and be available for download from the PacIOOS website. This is an easy and accessible format that will be available to all state and county agencies, as well as the general public.

We also produced estimates for the years 2030 and 2075, in response to DLNR"s request for additional intermediate values, as the original project's scope was limited to estimating shoreline change for only the years 2050 and 2100.

DLNR identified the need for erosion layers as hazard information for use in producing the Hawaii ICAC report. So, through dealings with ICAC, all directors of local planning departments (and other departments) have access to, and are providing feedback on, the display format of erosion layers on the PacIOOS website. The involvement with ICAC ensures that the erosion estimates produced from this study will be an integral part of the ICAC vulnerability assessment and report, so that the Hawaii State legislature can use these findings to assist in their decision-making process for future legislation.

5. Organization and Approach

This project continues development of an easily transferrable method for estimating future exposure to erosion, which includes the effects of increased SLR. In our approach, we began by focusing on finishing development of the model and application on ten test sites throughout the Hawaiian Islands. These sites were selected to represent the various wave regimes, geologic settings, and density of urban development found throughout the islands. After model completion and analysis, we submitted our findings for publication in a peer-reviewed journal (Anderson et al., 2015) to ensure that our methods and findings were scientifically sound. We then focused heavily on applying the model to all sandy shorelines of Kauai Island (Figure 1), except the Na Pali Coast where steep cliffs limit accessibility to the shoreline.

The following sections outline the data used in modeling, the modeling procedure itself, and our approach to transforming modeling results into usable GIS-compatible hazard layers.

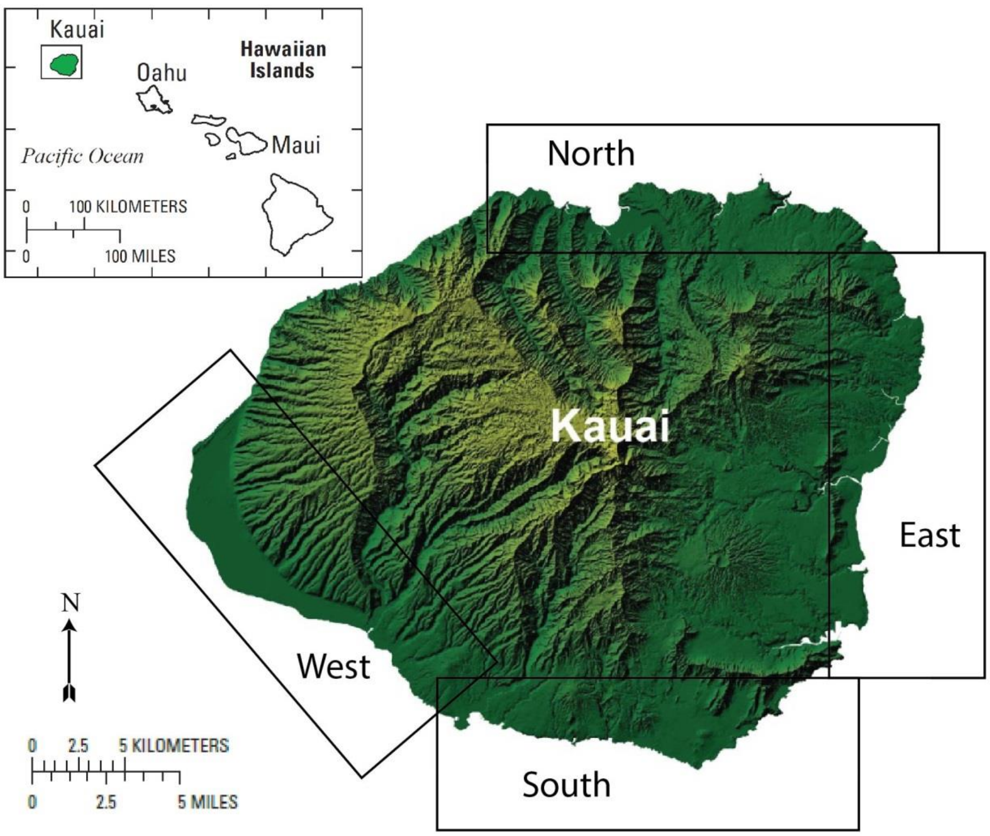

Figure 1. The island of Kauai is located at the northwest end of the main Hawaiian Island chain. Erosion analysis is performed on all sandy shorelines of the island, except the Na Pali Coast where sleep cliffs allow only intermittent pocket beaches that are not accessible by land vehicles. Summary statistics are provided for the four defined regions: North, East, South, and West Kauai.

5.1. Historical shoreline change

Historical shoreline locations for Kauai beaches were identified by University of Hawaii researchers as part of a previous study (Fletcher et al. 2013). Shoreline positions were extracted from high-resolution vertical aerial images and NOAA topographic charts. Roughly shore-normal transects, spaced 20 m apart, were cast. Along each transect, the relative positions of the shorelines were recorded to create a time series of shoreline positions (Figure 2). Weighted least squares regression is then used to determine the long-term trend of shoreline movement over time. Shoreline positions at each transect were translated to a new origin to condition the data matrices in the numerical procedures. The new origin is defined as the mean of all shoreline positions weighted by the data uncertainty.

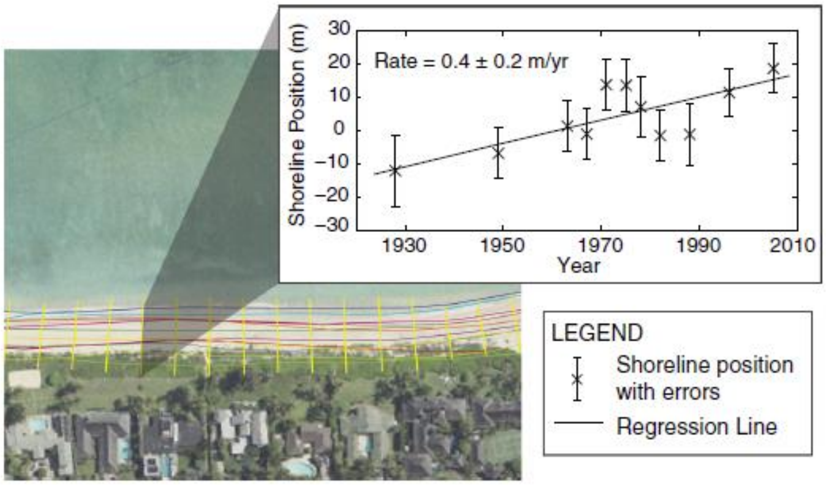

Figure 2. Linear regression is used to find the historical trend of shoreline positions over time (and its uncertainty) along transects spaced 20 m apart (yellow lines) (from Anderson et al. 2015). This figure illustrates an advancing shoreline (positive rate).

The uncertainty for each shoreline position was estimated from seven different sources of error. The range of error sources is shown in Table 1. Variations in source errors are due to variable physical factors (e.g. seasonal fluctuations, tides), and uncertainties in measurement and processing (e.g. digitizing error, rectification error). The largest data errors are found at beaches with large seasonal oscillations due to varying wave regimes along north- and west-facing shores (Table 2, right column). A summary of the shoreline data used for each region of Kauai is shown in Table 2.

Table 1. Range of historical shoreline position errors for Kauai (adapted from Fletcher et al., 2013).

Source of error	Magnitude range (m)
Seasonal error (*Es*)	± 2.5–19.9
Tidal error (*Etd*)	± 2–6
T-sheet conversion error (*Ec*)	± 1.0–13.8
Digitizing error (*Ed*)	± 0.8–9.7
Pixel error (*Ep*)	± 0.5–3.41
Rectification error (*Er*)	± 0.0–7.3
T-sheet plotting error (*Ets*)	± 5.1

Table 2. Shoreline data used in the historical shoreline change modeling typically cover a period of about 80 years. The number of transects (20 m spacing) vary between study areas of different lengths.

Region	No. Transects	No. Hist. Shorelines	Timespan	Data Errors (m)
North Kauai	1104	5 – 11	1927 – 2008	5.71 – 29.06
East Kauai	867	3 – 9	1927 – 2008	5.95 – 13.32
South Kauai	421	4 – 8	1926 – 2008	5.72 – 9.10
West Kauai	1307	4 – 9	1926 – 2006	5.73 – 24.68

5.2. Beach profiles

Surveys of cross-shore beach profiles were performed by researchers at the University of Hawaii Coastal Geology Group between 2006 and 2008. The survey method follows Gibbs et al. (2001). Surveys were conducted semi-annually at 27 locations on Kauai (Figure 3). Morphologic features along each profile, such as the vegetation line, berm crest(s), and the beach toe, were recorded during each survey. The beach toe, or base of the foreshore, is used to determine the position of the shoreline location (e.g., Fletcher et al., 2003).

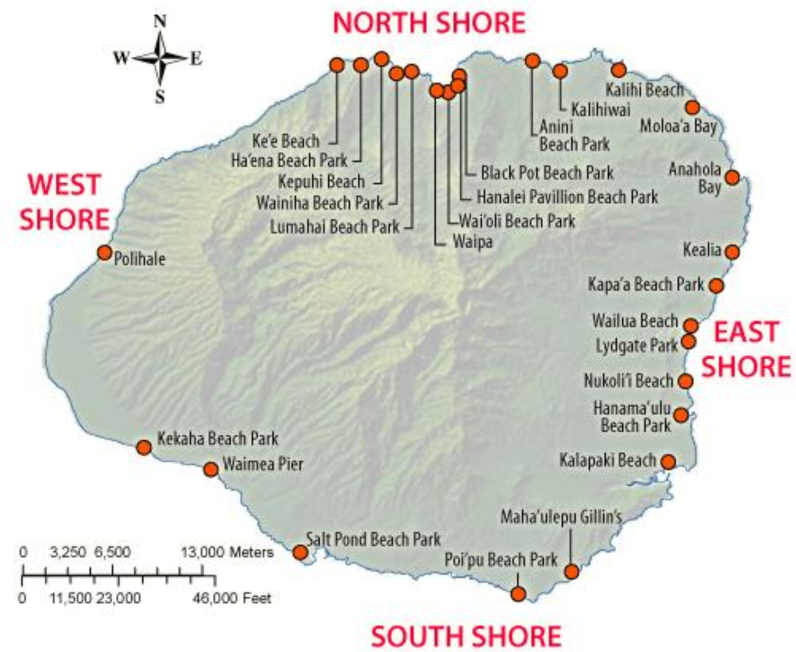

Figure 3. Locations where semi-annual beach profile surveys were conducted.

The presence of shallow fringing reefs often prevents profiles from extending seaward past the depth of closure, or depth at which water movement ceases to significantly alter the sandy bottom shape. In these situations, the convention of Cowell and Kench (2000) is followed, in which the intersection of the reef platform with the sandy beach is used as the effective depth of closure.

The nearshore beach slope of the active profile, defined here as the slope between the effective closure location and the beach toe, is estimated for each profile location. Cubic splines are used to interpolate between measured beach slopes alongshore. A summary of nearshore beach slopes is provided in Table 3.

Table 3. The average nearshore slope, tanβ, and its standard deviation for each profile location.

Profile location	tanβ ± std [× 10^{-2}]	Profile location (continued)	tanβ ± std [× 10^{-2}]
Ke‘e Beach	4.76 ± 0.57	Kealia Beach	2.61 ± 0.10
Ha‘ena Beach Park	4.48 ± 0.32	Kapa‘a Beach Park	4.86 ± 1.07
Kepuhi Beach	5.57 ± 0.40	Wailua Beach	4.07 ± 0.26
Wainiha Beach Park	5.63 ± 1.10	Lydgate Beach Park	3.51 ± 1.00
Lumahai Beach Park	5.92 ± 2.22	Nukoli‘i Beach	3.15 ± 0.80
Waipa	6.94 ± 1.60	Hanama‘ulu Beach Park	1.74 ± 0.15
Wai‘oli Beach Park	2.00 ± 0.35	Kalapaki Beach	2.24 ± 0.32
Hanalei Pavilion	1.84 ± 0.29	Maha‘ulepu Gillin’s	6.22 ± 1.37
Black Pot Beach Park	2.19 ± 0.43	Po‘ipu Beach Park	8.37 ± 0.72
Anini Beach Park	6.17 ± 1.14	Salt Pond Beach Park	3.60 ± 0.16
Kalihiwai	4.08 ± 0.42	Waimea Pier	4.20 ± 0.32
Kahili Beach	2.90 ± 0.92	Kekaha Beach Park	5.04 ± 1.06
Moloa‘a Bay	4.55 ± 0.15	Polihale	3.64 ± 0.53
Anahola Bay	2.91 ± 0.23		

5.3. Projected sea level rise

The IPCC future sea level projections for representative control pathway 8.5, the "business-as-usual" scenario, are used as model input (Figure 4). For simplicity, the projection is assumed normally distributed and centered about the projected IPCC median estimate, with variance defined as the square of the average distance between the median and the IPCC upper and lower limits of the "likely" range (Church et al., 2013).

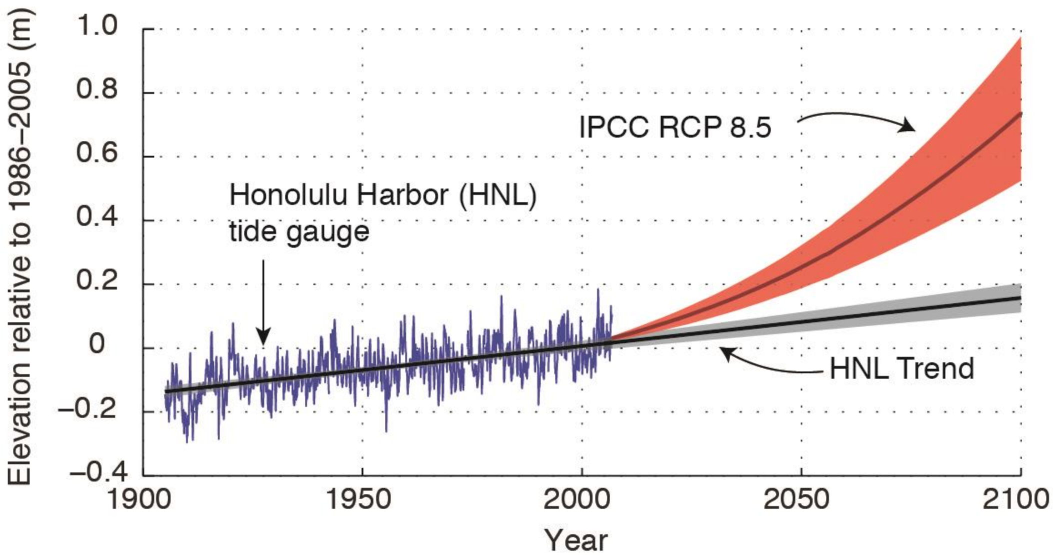

Figure 4. The IPCC RCP 8.5 estimate of future sea level is shown with the Honolulu Harbor tide levels. The extrapolated trend of past Honolulu sea level is shown for comparison with the IPCC estimates.

5.4. Shoreline change model

Future shoreline position is estimated by combining historical shoreline trends with the Davidson-Arnott geometric model of shoreline response to increased sea level (Davidson-Arnott, 2005). The method is thoroughly presented in Anderson et al. (2015), so only a brief description is provided here. The shoreline change model is given by

$$\Delta y = r(t_f - t_o) - (S_f - S_{hist}) / \tan\beta \tag{1}$$

where Δy is the net change ($-\Delta y$ indicates retreat) in shoreline position between initial time t_o and future time t_f, r is the historical trend, $(S_f - S_{hist})$ is the difference between the IPCC projected sea level and the extrapolated Hawaii sea level at time t_f, and $\tan\beta$ is the slope of the submerged portion of the active beach profile.

Probability density functions are created for r, $(S_f - S_{hist})$, and $\tan\beta$, and combined numerically to produce a probability distribution for each projected shoreline position at the specified future time.

5.2. Creating shoreline change vulnerability layers

A probability distribution of shoreline position is produced by the model at each transect spaced 20 m apart. Thus, by selecting the location that corresponds to a desired probability value, we create spatial contours of erosion hazard risk. For this study, we worked with our partner, DLNR, to identify two probability values of interest: 1) the 50th percentile (median) and 2) the 80th percentile. Model layers were edited and checked for quality assurance, and metadata was added to each GIS layer.

6. Project Results

Layers of estimated exposure to future erosion are available for viewing on the PacIOOS website http://www.pacioos.hawaii.edu/shoreline/slr-icac/. The site is currently password protected until the final ICAC report is completed in late 2017. Figure 5 shows an example of the viewer for a portion of shoreline along Kauai's north shore. After discussion with DLNR, University of Hawaii Sea Grant Extension Faculty, the Hawaii Office of Planning staff, and after hearing feedback from some ICAC members, only the 80th percentile probability contours are shown for each desired year. This decision was made to reduce potential confusion by users. The 80th percentile values are a more conservative estimate (from a safety standpoint) than the 50th percentile contours. However, the 50th percentile probability contours were provided to DLNR as originally agreed upon.

Figure 5. Projected erosion hazards (80th percentile probability contours) are shown for a portion of north Kauai for the years 2030, 2050, 2075, and 2100. The line indicates that there is an 80% probability that no erosion will occur landward of the line.

The average rate of shoreline change for each region is shown in Table 4. All regions show a negative average rate, which indicates shoreline retreat. Model results suggest that, on average, shorelines will continue to retreat at increasing rates into the future. This is a result of projected increases in SLR rates. As SLR rate increases in the future, model results indicate that the percent of shoreline that is retreating will also increase (Table 4). The model assumes that sandy beaches can erode indefinitely (that inland areas are "erodible"), so predicted future rates do not account for areas where, say, a beach erodes to the base of a cliff, then stops eroding. Thus, the average rates represent erosion potential if the land were erodible. Likewise, the percentage of retreating shoreline includes beaches that will be completely lost to erosion.

Table 4. Historical and future predicted shoreline change trends for each region of Kauai, Hawaii (negative rates indicate retreat).

Region	Length of Shoreline (km)	Year	Average Rate ± Std (m/y)	% Retreating	% Advancing
North	22.1	Historical	–0.11 ± 0.01	78	22
		2050	–0.24 ± 0.01	89	11
		2100	–0.35 ± 0.01	94	6
East	17.3	Historical	–0.16 ± 0.01	80	20
		2050	–0.33 ± 0.01	94	6
		2100	–0.48 ± 0.01	98	2
South	8.4	Historical	–0.17 ± 0.01	83	17
		2050	–0.27 ± 0.01	95	5
		2100	–0.36 ± 0.01	100	0
West	26.1	Historical	–0.02 ± 0.01	60	40
		2050	–0.15 ± 0.01	75	25
		2100	–0.26 ± 0.02	82	18

7. Analysis and Findings

Results indicate that more shorelines on Kauai Island will experience retreat, and at increased rates, through the end of this century with climate induced SLR under the "business-as-usual" emissions scenario. Compared with historical extrapolation alone, the estimated amount of projected net shoreline recession at least nearly doubles by mid-century, for all regions of Kauai (Table 5). The west Kauai region shifts from a currently balanced distribution of retreat and advance, to a dominantly erosive region by mid-century. However, the amount of estimated net shoreline change varies greatly within each region.

Table 5. Mean projected net shoreline change (±std) and range of net change for each study area shown based on historical extrapolation only, and the total net change with increased rates of SLR.

Region	Timespan	Historical extrapolation only		With increased SLR	
		Average net change (±std) (m)	Range of net change (m)	Average net change (±std) (m)	Range of net change (m)
North	2005–2050	-5.1 ± 0.6	-26.1 to 31.5	-8.9 ± 0.7	-30.2 to 23.0
	2005–2100	-10.8 ± 1.0	-55.1 to 66.5	-24.0 ± 1.2	-69.3 to 37.0
East	2005–2050	-7.0 ± 0.5	-37.8 to 28.7	-12.2 ± 0.6	-44.1 to 23.0
	2005–2100	-14.9 ± 0.8	-79.7 to 60.7	-32.8 ± 1.0	-101.6 to 40.8
South	2005–2050	-7.6 ± 0.4	-38.3 to 8.8	-10.6 ± 0.5	-42.8 to 5.8
	2005–2100	-16.0 ± 0.6	-80.8 to 18.6	-26.4 ± 1.0	-96.6 to 9.5
West	2005–2050	-0.8 ± 1.0	-68.6 to 88.7	-4.8 ± 1.3	-72.5 to 84.7
	2005–2100	-1.8 ± 1.7	-144.8 to 187.3	-15.5 ± 2.2	-158.5 to 173.5

8. Conclusions and Recommendations

We found that chronic erosion will increase in geographic scope and intensity on Kauai Island, Hawaii. The method that we created is easily portable to other locations that have a historical record of shoreline imagery, and measures of cross-shore beach shape. While the model is simple, it is beneficial in identifying areas that are highly exposed to coastal erosion over the current century. However, because of the many sources of uncertainty (e.g. seasonal fluctuations, tides, measurement uncertainty), it is best to look at more than one probability contour to identify the amount of uncertainty in the predictions. The model also assumes that all inland areas are erodible, so inclusion of a geologic map layer in any analysis is recommended.

Model results suggest that projected increases in SLR rates following the IPCC "business-as-usual" emissions scenario will cause 1) more shoreline to become erosive and 2) currently retreating shorelines to retreat at an increased rate, especially in the second half of the current century. The amount of recession varies greatly alongshore, so we recommend looking at projected hazard lines on a map to identify geographic regions that may be exposed to future erosion.

Government representatives and outreach specialists from DLNR, Sea Grant College Program, and the ICAC raised concerns regarding the presentation of model results. It is a priority for them to display the model results accurately, while taking into account the sensitivity of the public when viewing a model that might show their homes completely eroded away. Thus, we have taken extra care in providing layers that meet their needs, and revising wording to clearly explain what the model results represent. This issue caused initial delays in product development, yet highlights the importance of public outreach and education, especially in the areas of scientific modeling and model uncertainty.

As a continuation of this study, we are producing erosion hazard layers for other Hawaiian Islands in support of the ICAC initiative. Future improvements could be made in the geometric model of shoreline response to SLR, adding new shorelines to the historical shoreline analysis, incorporating the effects of underlying geology into future erosion estimates, and updating future sea level projections as new studies are completed.

9. Management Applications and Products

The probability contours of future erosion hazard are a valuable resource for identifying potential vulnerability of assets. The GIS layers of erosion hazard can be easily viewed and downloaded from the PacIOOS website to identify critically vulnerable natural and cultural resources that fall within the erosion hazard zones.

The regional average findings, which indicate significant increases in the amount of estimated future erosion hazard, highlight the need for adaptive management planning. Erosion hazards produced from this study will be used in an environmental and economic vulnerability assessment that will be reported in the ICAC SLR impacts report. We worked primarily with administrators within the DLNR Office of Conservation and Coastal Lands (OCCL) to identify needed information for improved decision-making. We also attended all ICAC meetings and presented our hazard modeling methods to the state legislators and heads of state government departments who are members of the ICAC committee. We also answered questions about SLR-related hazards and provided input on how to appropriately use the scientific findings (including modeling limitations) for future planning and projects.

The probability-based approach also provides added flexibility in the decision-making process, where coastal managers can act according to differing levels of risk (determined by probability values). For example, Spirandelli et al. (2016) used probability contours to create discrete zones of confidence in model projections. The method of estimating exposure to coastal erosion is also transferrable to other locations, and is especially useful for highly diverse geologic settings, such as reef environments, that are otherwise difficult to model.

10. Outreach

The following journal publications resulted from this study.

Anderson, T.R., C.H. Fletcher, M.M. Barbee, L.N. Frazer, and B.M. Romine (2015). Doubling of coastal erosion under rising sea level by mid-century in Hawaii, *Natural Hazards*, 78(1): 75–103, doi:10.1007/s11069-015-1698-6.

Anderson, T.R., C.H. Fletcher, and M.M. Barbee (2015). Coastal erosion hazards due to higher sea level: a simple hybrid historical/geometric model. In P. Wang, J.D. Rosati, and J. Cheng (Eds.), *The Proceedings of the Coastal Sediments 2015*. Paper presented at the Eighth International Symposium on

Coastal Engineering and Science of Coastal Sediment Processes, San Diego, 11–15 May. Hakensack, NJ: World Scientific.

Spirandelli, D.J., T.R. Anderson, R. Porro, and C.H. Fletcher (2016). Improving adaptation planning for future sea-level rise: understanding uncertainty and risks using a probability-based shoreline model, *Journal of Planning Education and Research*, doi: 10.1177/0739456X16657160.

Four oral presentations and one poster presentation was given at scientific conferences. The presentations were delivered at: the American Geophysical Union Fall Meeting in San Francisco, CA by T. Anderson (2014); the Geological Society of America Annual Meeting in Vancouver, BC by C. Fletcher (2014); the Association of Collegiate Schools of Planning Annual Conference in Houston, TX by D. Spirandelli (2015); Coastal Sediments Symposium on Coastal Engineering and Science of Coastal Sediment Processes by T. Anderson (2015); and the Geological Society of America Annual Meeting in Maryland by C. Fletcher (2015).

Study methods were presented in talks at the first two meetings of the Interagency Climate Adaptation Committee by C. Fletcher; and at the PICSC Climate Science Symposium by T. Anderson.

In March, 2015, a press release summarizing recently published results (Anderson et al., 2015) lead to print, television, and radio dissemination of the study results to the general public.

Many in-person meetings have taken place with the Head of DLNR OCCL and Sea Grant Extension Faculty regarding erosion model result format. Additional meetings occurred with DLNR staff, Sea Grant faculty, and PacIOOS staff regarding presentation of results in the web viewer. Over the last year, we have met several times with employees from TetraTech, the consultant hired to help organize the ICAC meetings and report. We were also present at all ICAC meetings and provided information on coastal erosion modeling to ICAC members, consisting of state legislators, and heads of state agencies such as the Departments of Transportation, Planning, and Education.

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